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PREFABRICATED TILT-UP CONCRETE PANELS FOR BLAST RESISTANT DESIGN

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Prefabricated Tilt-up Concrete Panels for Blast Resistant Design

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ABSTRACT

Engineering research efforts in the area of blast-resistant design is a priority of many government, military, and civilian organizations. Prefabricated tilt-up panels have become a very common method for conventional construction. This effort will present the development of an analytical model for creating static resistance functions which can be used in a single degree of freedom (SDOF) dynamic model. The results of the SDOF model can be used to predict and design the response of prefabricated tilt-up panels as blast walls. The paper will describe the performance of tilt-up panels for blast resistance using analytical models and full-scale field tests using live explosives. The results of the analytical dynamic model are verified using the field experiments, and the procedure is implemented into a user-friendly engineering design and analysis code, Air Force Wall Analysis Code (AFWAC).

INTRODUCTION

Prefabricated tilt-up panels have become a common method of today's construction for benefits provided by erecting structures with high levels of quality assurance provided from the casting yards and for their speed of assembly. The use of these panels is widespread among civilian projects, and has gained some acceptance but has not yet been implemented very often for military or government facilities due to the lack of data for blast response. There is a need to develop engineering prediction and design methods to expand the usability of prefabricated tilt-up panels. To this end, full-scale testing has been done at the Air Force Research Laboratory (AFRL), Airbase Technologies Division, Force Protection Branch, Engineering Mechanics and Explosive Effects Research Group at Tyndall Air Force Base, Florida in order to show that tilt-up panels can be a viable option for many government and military facilities. Included in this effort is a description of the full-scale blast testing; and an engineering level analysis method for predicting response of the concrete members utilizing a single degree of freedom (SDOF) model.

ANALYTICAL MODEL

In blast-resistant design and research, structures are often analyzed using an SDOF analytical model to approximate structural response [1, 2, 3]. The SDOF methodology involves simplifying a structural design or component down to a single degree of freedom which can be analyzed efficiently. This is done by assuming a deformed shape of the system. The assumed shape most often comes from static deflection analysis under uniform loading. The point where the maximum deflection of the assumed static deflection occurs correlates directly to the SDOF response prediction. The assumption is that the deflected shape is the same at all times and thus, the entire system can be modeled by the single point motion.

The response of the system is then predicted using an explicit set of equations to solve the equation of motion. The traditional SDOF model used in structural dynamics uses a mass-spring system with an externally applied force. This is still the basic premise in blast design and research, except that the spring stiffness, k, requires more definition in order to account for elastic and plastic behaviors. The prevailing method for defining the resistance to motion of a system is to define the static resistance function. The static resistance function is defined by the load-deflection curve of a system or component under a quasi-static load where the load is the resistance of the structural component at the given displacement. In the elastic range, it is clear that the spring stiffness, k, correlates to the structural component stiffness, or modulus. The assumption employed in the use of the static resistance function is that the spring stiffness, k, can be correlated to a load resistance at the given deflection which captures the details of the structural response beyond the elastic range.

Often SDOF models are done with simplified versions of the static resistance function taking into account only an elastic and perfectly plastic region. But more detailed static resistance functions are able to provide higher quality input for the SDOF response. There are two ways of achieving a more detailed analysis; through laboratory testing of the static response under a specific loading type (i.e. flexural, compressive, tensile, etc.), or develop a higher quality engineering level static resistance function utilizing engineering mechanics. Since laboratory testing of structural components is expensive, development of material model load-deflection relationships are needed in order to cost-effectively analyze prefabricated tilt-up panels. For the SDOF analytical predictions of the prefabricated tilt-up panels used in the field tests, an engineering mechanics model of the compressive strength is employed to create a static resistance function which is then implemented into the SDOF methodology.

The analysis which was performed on the prefabricated tilt-up walls was done using a program created specifically for this purpose. The program is essentially the marriage of two codes; one which performs the mechanics of the concrete failure and creates a resistance function, and one which implements the resistance function into an SDOF.

MECHANICS OF MATERIALS FOR RESISTANCE FUNCTION

The analytical model described herein is developed using a mechanics of materials approach. The major concept employed is that a fiber analysis scheme, also known as section analysis, often utilized in earthquake engineering applications [4] is utilized to develop the moment-curvature definition for the structural walls, and then implemented as the resistance function in the SDOF. The moment-curvature relationship can be transformed into the load-deflection relationship based on a few assumptions. The load is calculated from the moment based on the member geometry, while the deflection can be formed by integrating the curvature to compute the mid-span deflection. First, the moment-curvature scheme is discussed.

The moment-curvature response uses a mechanics of materials approach to incrementally determine the moment-curvature relationship for non-linear analyses of a given tilt-up panel. The moment-curvature scheme is dependent upon the concrete constitutive properties, the steel reinforcement properties, the dimensions of the given concrete member, and the axial loading condition. Figure 1 shows examples of the material models that are fundamental to this analysis.

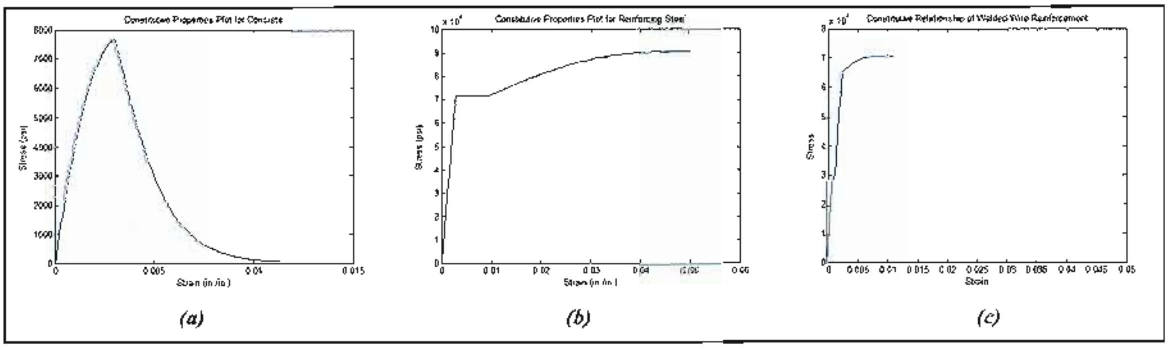

Figure 1 Constitutive Relationships; (a) normal concrete, (b) steel rebar, and (c) drawn steel wire

As shown in Figure 2 if the equilibrium condition is defined, then the stress and strain distributions can be used to define the moment and curvature relationships. The equations mechanics for finding the moment and curvature are:

$$M = \sum_{m=1}^{\#\text{layers}} f_m A_m y_m$$

$$\varphi = (\varepsilon_t - \varepsilon_b)/h$$

where f_m is the stress in the layer, A_m is the area of the layer, y_m is the distance from the bottom of the cross section, and h represents the overall height of the cross-section as depicted in Figure 2. The moment is the couple of the internal forces, and the curvature is defined by the slope of the strain distribution. The load-deflection relationship which is used to define the static resistance function may then be found. The load is produced as an evenly distributed pressure which creates the moment condition based on the support conditions. Likewise, the deflection can be calculated from the curvature based on the support conditions.

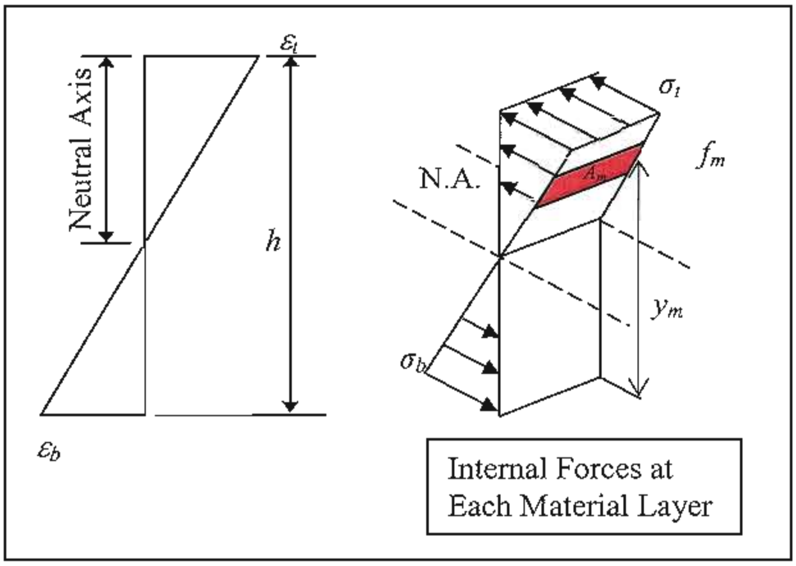

Figure 2 Stress and Strain Diagrams

MATERIAL MODELS

The moment-curvature scheme is dependent upon the concrete constitutive properties, the steel reinforcement properties, the dimensions of the given concrete member, and the axial loading condition. In order for the non-linear method to create an accurate SDOF response, the material models utilized must accurately represent the material response. Since the response of tilt-up panels is mostly dependent on a flexural loading or a combination of axial (load-bearing) and flexural loadings, an accurate compression material model for concrete is vital.

The compression model used for this study is an analytical model that had evolved into a set of equations developed by Shah, Fafitas, and Arnold [5] based on several tests and analysis of previously existing analytical models. It is a non-linear approach to forming the constitutive model of concrete in compression. It is broken down into three regions; a linear elastic region, an ascending nonlinear region up to the peak stress, and then a descending region. The set of equations utilize several numerical constants which allow the model to capture the details of varying peak strains, confinement effects, and resulting changes to peak compressive stress as well as the hardening and softening regimes. For brevity, only the equations will be discussed.

The linear elastic region is defined as

$$f = \varepsilon_m E_c$$

where f is the stress, ε_m the corresponding strain, and E_c the elastic modulus which is defined by

$$E_c = 33\,\gamma^{1.5}\sqrt{f_c^{'}} \qquad \text{(English units, psi)}$$

$$E_c = 0.14\gamma^{1.5}\sqrt{f_c^{'}} \qquad \text{(SI units, kPa)}$$

γ is the unit weight of the concrete in pounds per cubic feet in English units and kg/m^3 in SI units. The ascending nonlinear portion, also referred to as repeat behavior, is

$$f = f_o\left[1-\left(1-\frac{\varepsilon}{\varepsilon_o}\right)^A\right]$$

where ε_o, f_o, and A are the peak strain, peak stress, and an empirical constant for the ascending nonlinear portion, respectively. These variables are defined by the following equations:

$$f_o = f_c^{'} + \left(1.15 + \frac{3{,}048}{f_c^{'}}\right)f_r \qquad \text{(English units, psi)}$$

$$f_o = f_c' + \left(1.15 + \frac{2,100}{f_c'}\right) f_r \qquad \text{(SI units, kPa)}$$

$$e_o = 1.027 \times 10^{-7} f_c' + 0.0296 \frac{f_r}{f_c'} + 0.00195 \qquad \text{(English units, psi)}$$

$$e_o = 1.491 \times 10^{-8} f_c' + 0.296 \frac{f_r}{f_c'} + 0.00195 \qquad \text{(SI units, kPa)}$$

$$A = \frac{E_c \varepsilon_o}{f_o}$$

and the confining pressure, f_r, in the presence of spiral reinforcement is expressed as

$$f_r = \frac{2A_s f_y}{d}\left(\frac{1}{s} - \frac{1}{1.25d}\right), \qquad 0 < s \leq 1.25d$$

in which A_s = the cross section area of the spiral wire; s = the spacing of the spiral (must be greater than zero to be valid); and d = the diameter of the confined core. The restriction on the spiral spacing is imposed due to observations that the confinement effects become negligible as the spacing is approximately $1.25d$.

For the descending part of the constitutive model,

$$f = f_o \exp\left[-k(e - e_o)^{1.15}\right]$$

In which k = a constant determined to match the descending portion, or what is referred to as post-peak behavior, of the constitutive curve. Through regression analysis, k has the following form:

$$k = 0.17 f_c' \exp(-0.01 f_r) \qquad \text{(English units, psi)}$$

$$k = 0.025 f_c' \exp(-0.00145 f_r) \qquad \text{(SI units, kPa)}$$

STATIC RESISTANCE FUNCTION

The SDOF scheme is a very efficient way to predict structural behavior; which, in turn, allows for more productive testing. With a degree of certainty, the SDOF analyses provide insight into the mechanics of a structural member. This insight helps define a threat level which will produce an adequate level of protection for the inhabitants of a structure.

One of the key features of a SDOF analysis is that the static resistance of a structural member is used to provide a resistance to dynamic movements. The static resistance function formulated here derives from the material models and uses a fiber analysis to define the load-deflection relationship as previously mentioned. The moment-curvature relationship is found by incrementally increasing the top-fiber strain and calculating the stresses required for equilibrium. The solution algorithm for the non-linear moment-curvature analysis is fairly straightforward. It implements the major features of any mechanics of materials approach; that is the compatibility, equilibrium, and constitutive conditions must be met. In this scheme, the compatibility condition, a strain distribution is assumed, the equilibrium condition is checked to make sure the compatibility condition provides equilibrium, and then the stress-strain distribution is used to find the moment and curvature. The algorithm for finding the moment-curvature is progressed by incrementing the top-fiber strain in the cross section. There are three main steps to the algorithm: (1) assume an equilibrium position of the neutral axis for the stress distribution; (2) calculate the material stresses for the assumed position; (3) check to see if equilibrium is satisfied with the assumed position of the neutral axis and iterate the assumed neutral axis position until equilibrium is found through a convergence check.

The abovementioned scheme produces a load-deflection relationship through material failure. Figure 4 illustrates the static resistance function which is developed using the techniques discussed in this paper. There are a couple of unique features for this resistance function. The first is the softening region as the welded-wire reinforcing cage yields. Secondly, there is a sudden drop in the resistance when the welded-wire reinforcement fails that corresponds with the peak resistance. The next region exhibits the yield plateau of the rebar followed by the rebar softening regime and failure. Overall response and efficiency of the developed SDOF are discussed in conjunction with the full-scale blast test results in the subsequent section.

The incremental and iterative scheme described above for formulating the static resistance function is summarized in Figure 3. The resulting static resistance function is then implemented into the SDOF dynamic model.

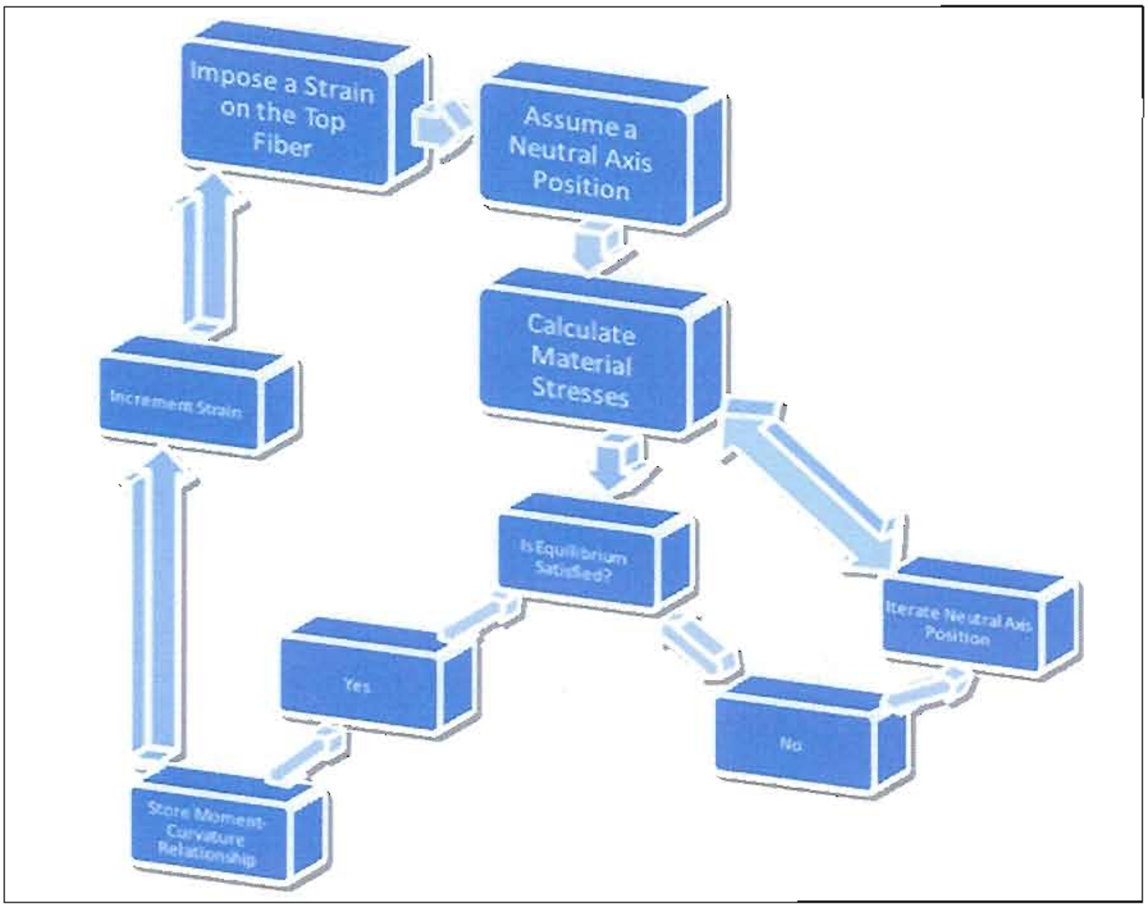

Figure 3 Program Flowchart

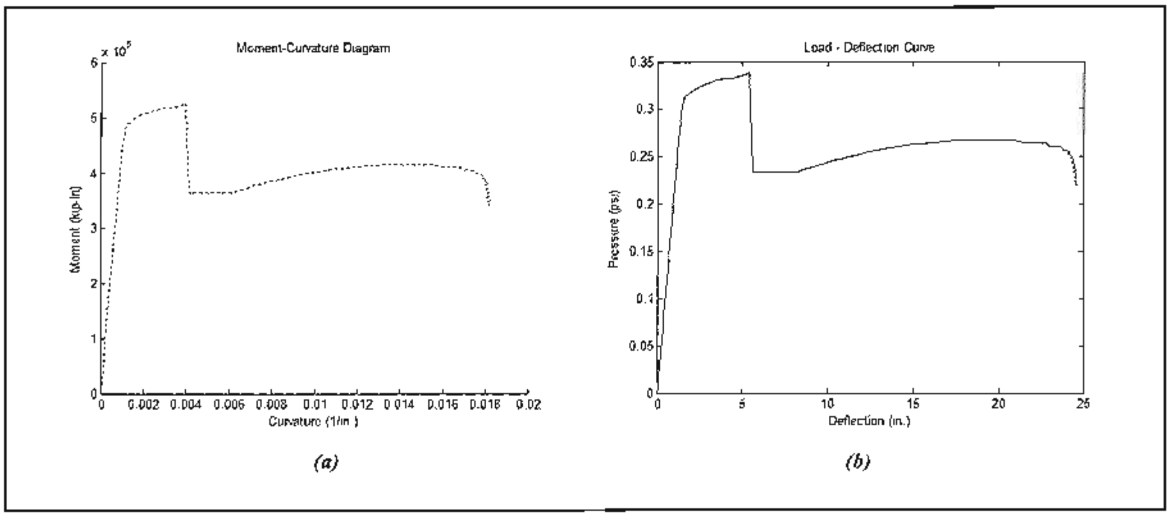

Figure 4 (a) Moment-Curvature and (b) Load-Deflection

LABORATORY EXPERIMENTS

To validate the model, laboratory experiments were purposed providing a comparison of analytical results to a theoretical wall section. Wall sections were cast with normal weight concrete having dimensions of 6 inches deep by 18 inches wide with one #4 rebar placed in the center of the section; the tested clear span was 120 inches. Figure 5 shows the comparison of the model and theoretical sample, in addition the sample was analyzed with the current methods of elastic perfectly plastic methods. Note the additional absorption capabilities of the section over the conventional method.

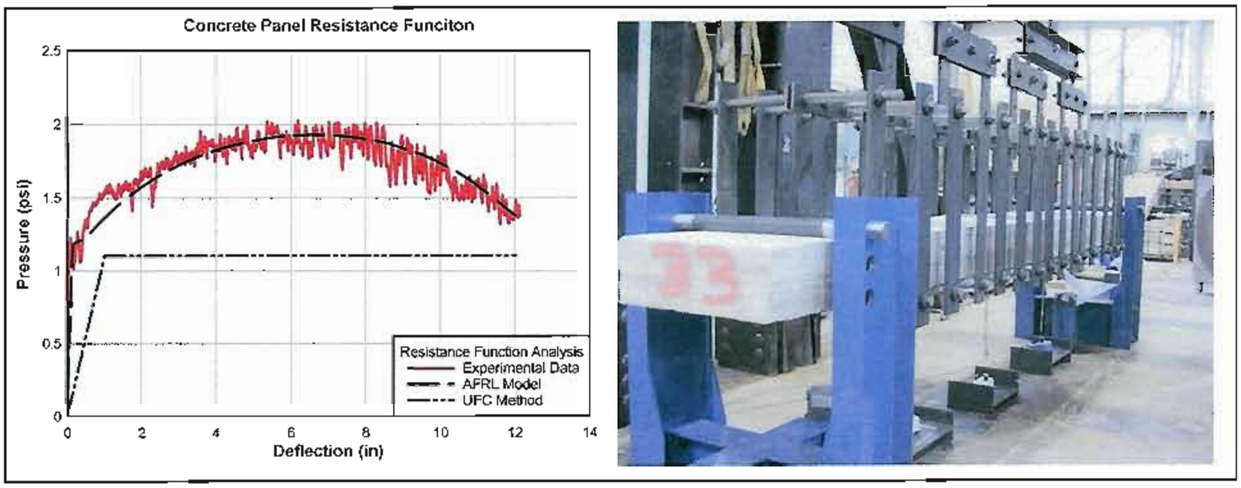

Figure 5 Static Resistance Function – Experimental vs. Analytical

FULL-SCALE BLAST TESTS

Pre-cast wall panels have been experimental tested will be compared to the analytical predictions using the SDOF model. The experimentally tested panels were made using normal concrete with W4xW4 welded-wire mesh and 8 - #4 rebars in the vertical direction of the wall. The rebars were placed at the center of the cross section with the wire mesh to one side, Figure 5.

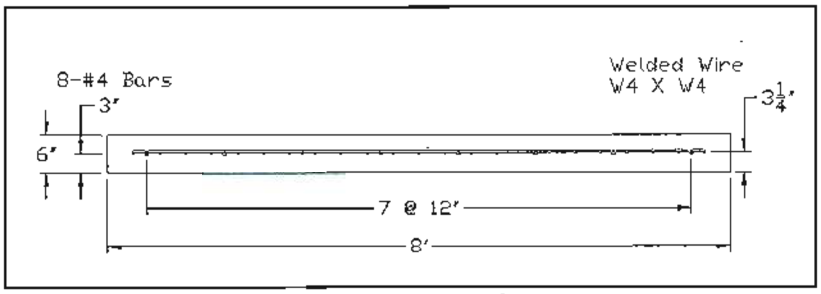

Figure 6 Panel Cross Section

Cylinders were cast with the panels and tested to have an average of compression strength of 7.56 ksi at 28 days. The experiment was constructed to supply simply supported conditions for the panel. Figure 6 gives a schematic of the test setup and details on the comparison gauge locations.

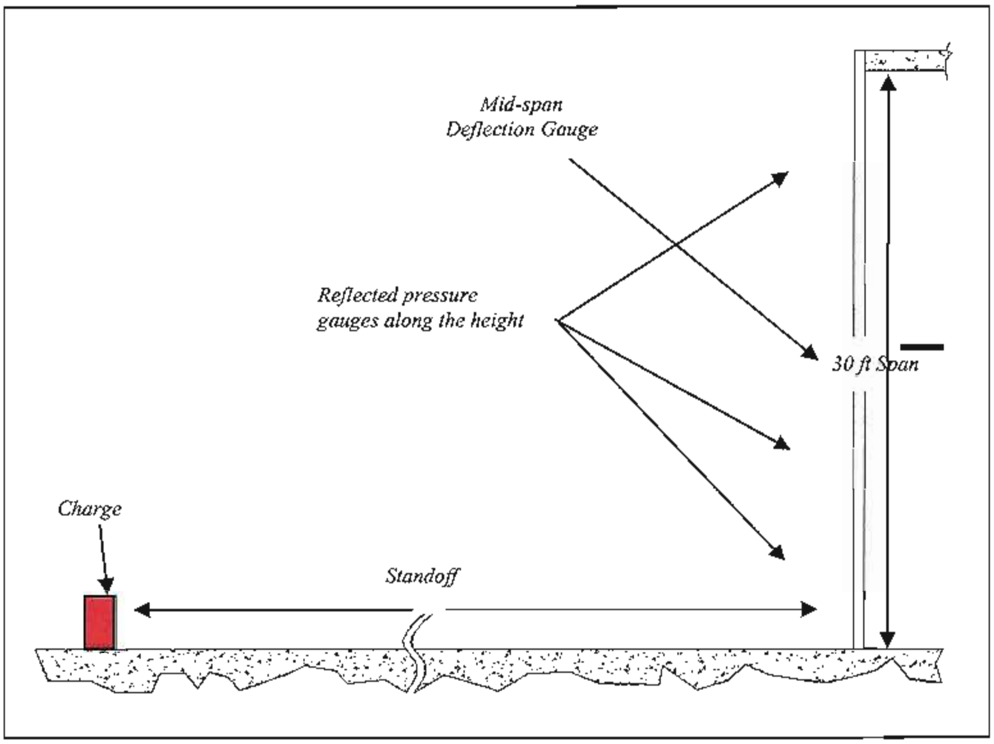

Figure 7 Test Setup

Four explosive experiments were performed with variable standoff distances and identical charge weights. By varying the standoff a multitude of responses were available in verifying the SDOF computations. Due to the frequency of the panels the negative phases of the blast loading were included to calculations. Figure 7 shows a typical pressure time curve from testing that was used in the SDOF modeling. For each experiment a different standoff distance was used giving four distinctive loading curves. Precast panels often require the inclusion of the negative phase loading due to the typical spans for which they are designed. The reason for this is that the natural frequency of the large panels is large enough that the panels are still reacting to the load and the negative phase helps pull the panel back. In typical systems, the exclusion of the negative phase is considered to be conservative or has little effect. But for large components like precast panels where the natural frequency is often larger than the duration of the applied load, the negative phase can have a noticeable effect. This is the case with the precast panels that were tested at AFRL. Exclusion of the negative phase load suggests that the panels might possibly fail; when in fact, the panels are well within their range of survivability due to the negative phase loading.

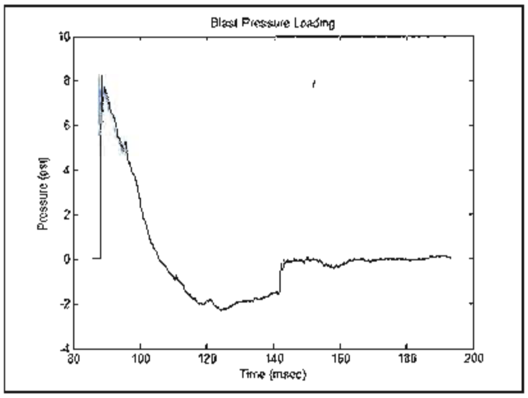

Figure 8 Blast Loading

In exploring the behavior of the panels, the predictive methods employed by the SDOF methodology provide very good correlation with the test results. The predicted responses are within about 5.42% as reported in Table 1.

Table 1. SDOF – Test Data Correlations

Test Series	SDOF Prediction (in)	Test Result (in)	% Difference
1	2.1034	2.1359	-1.52%
2	3.3709	3.5639	-5.42%
3	5.4014	5.4166	-0.28%
4	6.9204	6.8817	+0.56%

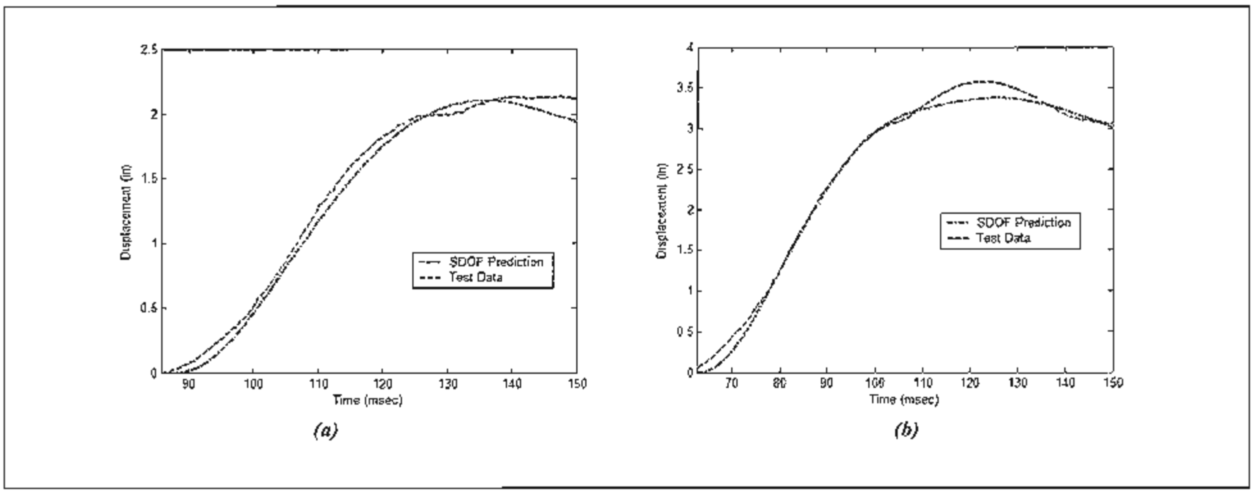

Figure 9 Overlay of SDOF Design Tool and Test Data; (a) Test 1, (b) Test 2

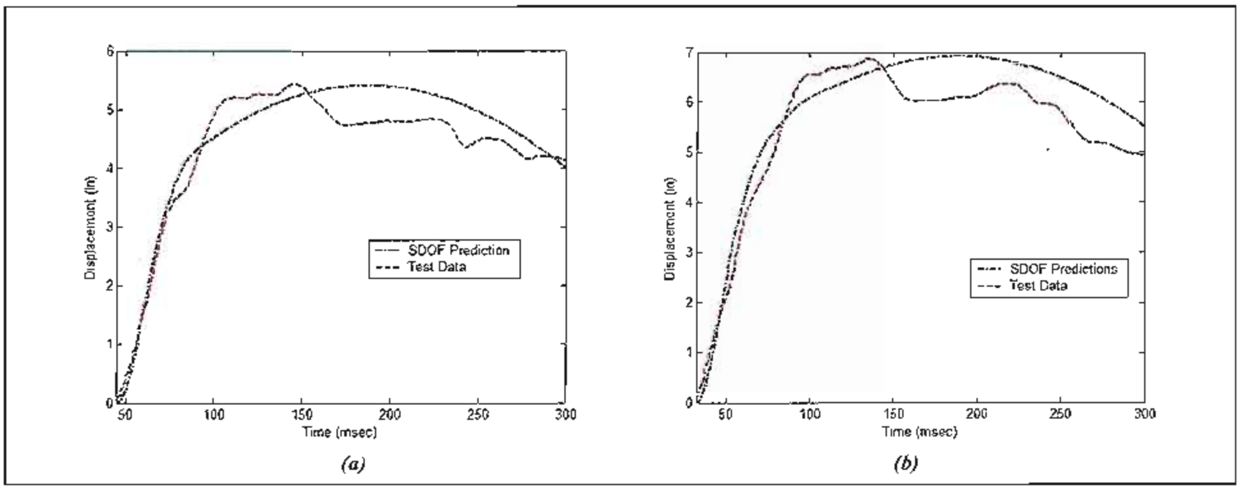

Figure 10 Overlay of SDOF Design Tool and Test Data; (a) Test 3, (b) Test 4

The SDOF results show good correlation with the test data. When analyzing the test data, there are some interesting oscillations which appear. It was determined that these oscillations were due to the test setup. While testing the precast wall panels, the deflection was measured through the use of scratch gauges placed at quarter points. These gauges were mounted to angles that were bolted into the side walls of the reaction structure. It is evident when viewing the high-speed video of the test results, that the blast loading on the structure causes the angles which the deflection gauges are mounted on to oscillate. The period of the angles is 49 ms, which is right in line with the period of the oscillations which appear in the test data. The effect is much more evident on test 3 and 4. As the deflection approaches the peak, there is a sudden shift in the slope of the curve. This corresponds with the gauge-mounted angles flexing in initially. There is then a subsequent peak corresponding to the angle flexing back toward the test wall matching the period of vibration for the angle.

The oscillations which occurred during the testing create spurious data in the results. Thus, having the results fall within an error in of 5.42% or less is deemed to be a very desirable result.

CONCLUSION

It is shown that the enhanced constitutive models employed in the derivation of the precast panel response produce excellent results that show excellent correlation with test results. Interesting features of the resistance function which is derived from this approach are enhanced material models featuring detailed material descriptions for concrete, steel, and welded wire reinforcement; and the ability to include axial loads (floor bearing loads). The SDOF tool developed here is proven to be useful tool for predicting the blast response of structures and may be easily implemented into a quick running PC-based code, such as the AFWAC program currently being developed by AFRL at Tyndall AFB.

As was assumed at the outset of this effort, precast concrete panels are a viable option for government and military construction and are suitable for providing adequate levels of protection in many cases. Care must be taken when designing precast panels, however. The benefits afforded by precast panels can also have adverse affects without a proper understanding of the mechanics involved in long spanning, slender components. Namely, the ability to build structures with longer spanning, slender components creates new issues which are not normally taken into account. These are mainly effects related to the natural frequency being close, if not longer, than the loading duration of most blast loads.

RECOMMENDATIONS AND FUTURE RESEARCH

It is recommended that welded-wire mesh be seriously considered when designing concrete structural elements. The welded-wire mesh provides good early resistance without changing the overall stiffness of the member. This is an important aspect in that the inclusion of welded-wire can give good resistance and allows for the dense mass of the concrete to provide momentum resistance without increasing the overall stiffness. The increase of stiffness can actually have adverse affects in that the frequency of the component increases and the component will lose the benefits of the negative phase loading.

Future work will investigate and better define the affects of the welded-wire reinforcement. Additional work is also underway to investigate the alteration of shape traditional shape functions used for SDOF calculations. All results are being fed into AFWAC. AFWAC is a PC-based analysis and design tool which AFRL has been developing in order to transfer results from AFRL research efforts to the end user.

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